PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. A-3673 GTRI/~~GIT~~ DATE 10 / 05 / 83

Project Director: John Gilmore ~~School/~~Lab EML

Sponsor: Martin Marietta

Type Agreement: Purchase Agreement No. ZD/958138

Award Period: From 9/19/83 To ~~12/16/83~~ 5/30/84 (Performance) ______ (Reports)

Sponsor Amount: This Change Total to Date

Estimated: $ ______ $ ______

Funded: $ 8,000 $ 8,000

Cost Sharing Amount: $ ______ Cost Sharing No: ______

Title: "Obstacle Avoidance Algorithem Development Report"

ADMINISTRATIVE DATA OCA Contact Frank Huff X4820

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Defense Priority Rating: None

Military Security Classification: ______
(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached ______ Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with N/A; none proposed.

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Date 6/25/84

ʼroject No. A-3673 — ~~School~~/Lab EML :

ncludes Subproject No.(s)

ʼroject Director(s) John Gilmore — GTRI / ~~GIT~~

ʼponsor Martin Marietta

Title "Obstacle Avoidance Algorithem Development Report"

Effective Completion Date: 5/30/84 (Performance) 5/30/84 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
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PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. A-3674 GTRI/~~GIT~~ DATE 10 / 05 / 83

Project Director: John Gilmore ~~School~~/Lab EML

Sponsor: Martin Marietta

Type Agreement: Purchase Agreement No. ZD/958142

Award Period: From 9/19/83 To ~~12/16/83~~ 3-15-84 (Performance) ______ (Reports)

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Cost Sharing Amount: $ ______ Cost Sharing No: ______

Title: Obstacle Avoidance Algorithem Development Report

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Defense Priority Rating: None

Military Security Classification: ______

(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached ______ Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with N/A; none proposed

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SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 6/25/84

Project No. A-3674 — ~~School~~/Lab EML

Includes Subproject No.(s) ____

Project Director(s) John Gilmore — GTRI / ~~GIT~~

Sponsor Martin Marietta; Orlando, FL

Title Obstacle Avoidance Algorithem Development Report"

Effective Completion Date: 4/16/84 (Performance) 4/16/84 (Reports)

Grant/Contract Closeout Actions Remaining:

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FINAL REPORT

GT Project Nos. A-3673 & A-3674

OBSTACLE AVOIDANCE ALGORITHEM DEVELOPMENT REPORT

By

John F. Gilmore

Prepared for

MARTIN MARIETTA

Under

Contract Numbers: ZD/958138 and ZD/958142

May 1984

GEORGIA INSTITUTE OF TECHNOLOGY

A Unit of the University System of Georgia

Engineering Experiment Station

Atlanta, Georgia 30332

1984

OBSTACLE AVOIDANCE ALGORITHM

1.0 Introduction

Tactical and strategic missions of the next decade will require aircraft to fly closer to the earth to avoid detection by sophisticated antiaircraft sensors which will detect active sensors. This flight at lower altitudes will necessitate automatic maneuvering to reduce pilot workload. In addition, attractive new avionics will compete with sensor pods for payload capacity. These problems make a covert, automated, single pod sensor an extremely important asset for piloting and weapon delivery.

A key performance aspect of the sensor pod will be its ability to perform terrain following, terrain avoidance, and obstacle avoidance. This report focuses on the development of an obstacle avoidance algorithm capable of detecting 1 meter wide, 61 meter ($\pm$15%) tall towers at ranges greater than 1.5 kilometers.

2.0 Requirements

Based on current sensor technology, the requirement to detect an obstacle of one meter width at a range greater than 1.5 kilometers means that the obstacle subtends an angle of 0.67 mrad. When a wide-field-of-view (WFOV) is employed for obstacle avoidance, there will frequently be less than one full sample per scan line across the obstacle. Though this presents a significant challenge to the signal processor, exploiting the vertical structure which a tower exhibits over a sequence of frames should provide a high confidence obstacle detection mechanism.

In order to accurately detect towers in visual imagery, their limited characteristics must be fully exploited. A priori tower information in a lower altitude scenario includes the following facts:

(1) The towers will be 61 meters ($\pm$ 15%) in height and one meter in width.
(2) The sensor will be flying at approximately 61 meters ($\pm$ 15%) and will therefore always be within 18 meters of the tower height.
(3) The tower must be detected at sufficient range to permit the aircraft to automatically avoid the tower without pilot intervention and without the aircraft being required to sustain more than 1g. This range is projected to be approximately 1.5 kilometers.
(4) The tower will be $1^{o}C$ above ambient air temperature.
(5) The imagery used is assumed to be heads-up, therefore towers will be vertical with respect to the horizon.

3.0 Algorithm Approach

Based upon the requirements defined in the previous section, a tower detection algorithm shown in Figure 1 was developed. The algorithm consists of four distinct sections: preprocessing, edge detection, prescreening and structural analysis.

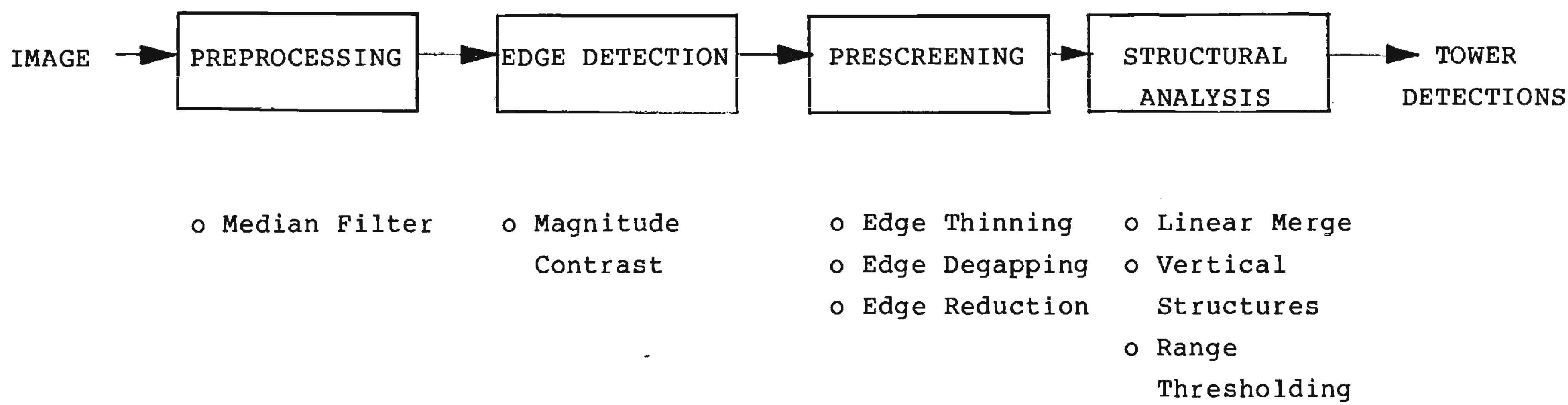

FIGURE 1. TOWER DETECTION ALGORITHM

3.1 Preprocessing

Preprocessing consists of enhancing the edge qualities of an image as well as removing random noise produced by the sensor. Median filtering is a nonlinear signal processing technique that accomplishes both of these goals. In a two-dimensional FLIR image, a median filter consists of a sliding window encompassing an odd number of pixels. In this manner, the center pixel is replaced by the median of the pixels within the window for each pixel in the original image.

There are various strategies for the suppression of noise using a median filter. One method is to apply a 3 by 3 window across the image and check for any significant signal loss. If none is detected, the filter size is increased to a 5 by 5 operator and applied to the original image. This process is continued until the filtering process begins to distort rather than enhance the image. For the Simulation and Test Lab (STL) database provided, a 3 by 3 filter proved to be optimal.

3.2 Edge Detection

The magnitude contrast algorithm proved to be the most viable approach in detecting edges in STL database imagery. The magnitude contrast algorithm consists of two processing stages: magnitude differencing and contrast evaluation. In magnitude differencing, the 3 by 3 operator shown below is applied to each pixel in an image to determine the magnitude of the largest pixel difference in the immediate neighborhood.

N1	N2	N3
N4	$P_{i,j}$	N5
N6	N7	N8

$$DIMAGE(I,J) = (\max[ABS(P_{i,j}-N_k)])$$

$$\text{for } k = 1,8$$

FIGURE 2. MAGNITUDE DIFFERENCE PROCESS

For each application of the magnitude operator, the neighboring N_k pixels are subtracted from the value of the center pixel, $P_{i,j}$. The largest absolute difference of the neighborhood is determined and assigned to the pixel location (i,j) in a magnitude difference image. Unlike the majority of gradient edge operators investigated, the magnitude operator is directional invariant and requires only a single application rather than eight separate direction filters (e.g. Sobel).

Contrast evaluation of the magnitude difference image is the second processing stage. The eight adjacent D_k neighbors of a centralized pixel, $P_{i,j}$, are averaged to form a neighborhood contrast measurement. This average is reduced by the value of the center pixel and placed into an edge image as shown below.

D1	D2	D3
D4	$P_{i,j}$	D5
D6	D7	D8

$$EIMAGE(I,J) = \frac{\sum_{k=1}^{8} D_k}{8} - DIMAGE(I,J)$$

FIGURE 3. CONTRAST EVALUATION PROCESS

Applying a contrast factor to the pixel average provides additional control over the edge strength produced. In its normal form, a factor of 1.0 is implied. By multiplying the pixel average by a factor greater than 1.0, weaker edges are eliminated from the segmentation. Decreasing the factor increases the number of low contrast edges produced and typically generates the internal structure of the objects within a scene. Training on a representative database determines the optimal contrast factor setting for a specific application.

The magnitude contrast approach to edge detection offers the potential of extracting weak, low contrast edges from an image. Sobel, Roberts, gradient and other edge filters investigated were also capable of identifying low contrast edges, but the threshold settings required to extract the edges also introduced massive amounts of false edge pixels, making the edge separation process impossible. A strength threshold on the magnitude contrast algorithm removes edge noise and clearly produces only solid edge lines. Additionally, it can be shown that the magnitude contrast algorithm approximates a second order edge derivative, thus determining low contrast points of inflection not detectable by other filters.

3.3 Prescreening

Prescreening examines the edges extracted by the magnitude contrast algorithm and performs three functions: edge thinning, edge degapping, and edge reduction. As an edge will typically have two points of inflection (one internal and one external to an object due to the nature of digital imagery), edge thinning attempts to reduce the edge area to a single pixel representation. Edge degapping bridges small pixel gaps between two edges of relative slope and merges the lines in a single edge length. The gap threshold value is usually one or two pixels. Edge reduction removes stray edge values by applying a predetermined length threshold (usually three pixels) that must be exceeded for a vertical edge to be considered a possible tower. The edge reduction threshold is range dependent and can easily be automated given accurate passive ranging data.

3.4 Structural Analysis

Once the edge image is prescreened to enhance consistent edges and eliminate stray noise edges, structural analysis is performed. A linear merge evaluation is made to link edges that may have exceeded the range of the edge degapping determination applied in prescreening but possess comparable slopes. In linear merge, an edge N is selected and its end point is compared to all edge start points to determine whether another edge is within a Euclidean distance of 7 pixel units. If an acceptable edge M is found, its slope is computed and compared to that of edge N. If edge M's slope is within $\pm$ 10% of edge N, the two edges are merged into a single edge representation. This process is repeated for all of the edges produced by the magnitude contrast algorithm.

Based upon an assumption of heads-up imagery, edges that are not within $\pm$ 45^{o} of true vertical are suppressed. Probabilistically speaking, this should have reduced the number of edges by a factor of 8:1 given a random edge distribution. But as most of the world is either horizontal with the earth or vertical toward the sky, an actual edge reduction of 4:1 is usually achieved.

Range thresholding attempts to apply a priori knowledge of possible tower heights (61 meters $\pm$ 15%) to a computed object range extracted through passive ranging. This information is used to determine a pixel length threshold which only a tower (or equally tall obstacle) edge should exceed. As the results of the passive ranging algorithm were not available for this work, the edge length average was computed and used as an arbitrary range threshold. This will be altered upon the availability of accurate obstacle ranging information.

4.0 Database

The obstacle avoidance requirements for the sensor and the characteristics of the towers to be avoided have been described in earlier sections. The only free parameters affecting algorithm performance relate to weather and environment. To demonstrate the obstacle avoidance performance required in high speed, low flying aircraft it is necessary to obtain or generate an image database of a one meter tower at ranges of 1.5 to 5 kilometers with a temperature delta of $1^{o}C$ over the ambient air temperature. Collection of such a sequential image database from a low-flying, high performance aircraft would be ideal, but simulated FLIR imagery collected from Martin Marietta's Simulation and Test Lab was projected to meet mission requirements.

Several problems existed with the Martin Marietta obstacle avoidance database, the most serious being a sixty day delay in providing simulated FLIR image to Georgia Tech. Originally, the analysis of the tower detection algorithm was to answer two important questions:

[1] What is the maximum automatic detection range as a function of atmospheric attenuation?

[2] What is the probability of detection and the probability of false alarm as a function of atmospheric attenuation?

The delivery delay combined with database deficiencies outlined below precluded the analysis required to address these questions.

The obstacle avoidance database imagery suffered from a number of deficiencies when compared to the original MUFFLIR database requirements. First, the simulation of FLIR imagery was quite poor, with no real contrast being exhibited by natural terrain anywhere within the imagery. Due to the thermal characteristics of a FLIR sensor, it is impossible to believe that no natural contrast would exist in a 66 image database. Second, through applying a histogram to the imagery, the poor contrast of the data was further confirmed by that fact that the imagery was actually less than seven bits rather than the required eight. Pixel values ranged from 0 to 116 and exhibited a single modal cluster constituting 90% of the pixel values. Third, no temporal obstacle ranging information was available. Approximate ranging to the center and corner points of an image was provided, but evaluation showed these values to be accurate within ± 100% of the actual range. Fourth, the point range data provided partitioned the database into the following range bins:

Range	Number of Images		Range
0	2	2	1000
100	0	3	1100
200	1	9	1200
300	1	4	1300
400	2	2	1400
500	7	2	1500
600	9	1	1600
700	4	2	1700
800	0	0	1800
900	13	1	1900
-	--	1	2000

As detection of towers must be achieved from a range of 1500 meters or greater, the database was not reflective of the MUFFLIR scenario as over 89% of the images did not exceed this range. When combined with poor FLIR simulation, detection in those images of an acceptable range by even a human observer was not possible. The conviction that a closure sequence from 5 to 1.5 kilometers would provide accurate detection performance still exists, but awaits testing with a representative database.

5.0 Results

The tower detection algorithm was run on the obstacle avoidance data to evaluate its performance. Figure 4. shows a simulated FLIR image produced by the Martin Marietta Simulation and Test Lab. Applying the magnitude contrast algorithm with a contrast factor setting of 0.1 produces the edge map shown in Figure 5. Because the magnitude contrast algorithm is directional invariant, a large number of edges are produced. As a heads-up display was assumed, all non-vertical edges were suppressed and a range thresholding factor of 50 pixels applied producing the tower detection results shown in Figure 6. The tower detection mask is overlayed on the original image in Figure 7. to demonstrate detection performance. Notice the "tower" detection in the lower left hand side of the image. The obstacle detected is actually a tree, but because of the sensor height, it is detected as an obstacle in the flight path plane. This is therefore not a false alarm in the sense that it is actually an obstacle that must be avoided in the same manner as the detected towers.

Of the imagery provided, four runs were identified as shown in Tables 1-4. STRA and STRH were effectively runs on the same tower configuration displayed in Figure 3. The tower algorithm accurately identified the towers in these runs and detected all other flight obstructing obstacles (i.e. trees) when given a contrast factor of 0.1. STRC was a one image run consisting of four targets but no towers. As expected, the algorithm failed to detect what would have been a false tower. STRF was an eleven image sequence of a small building next to a one

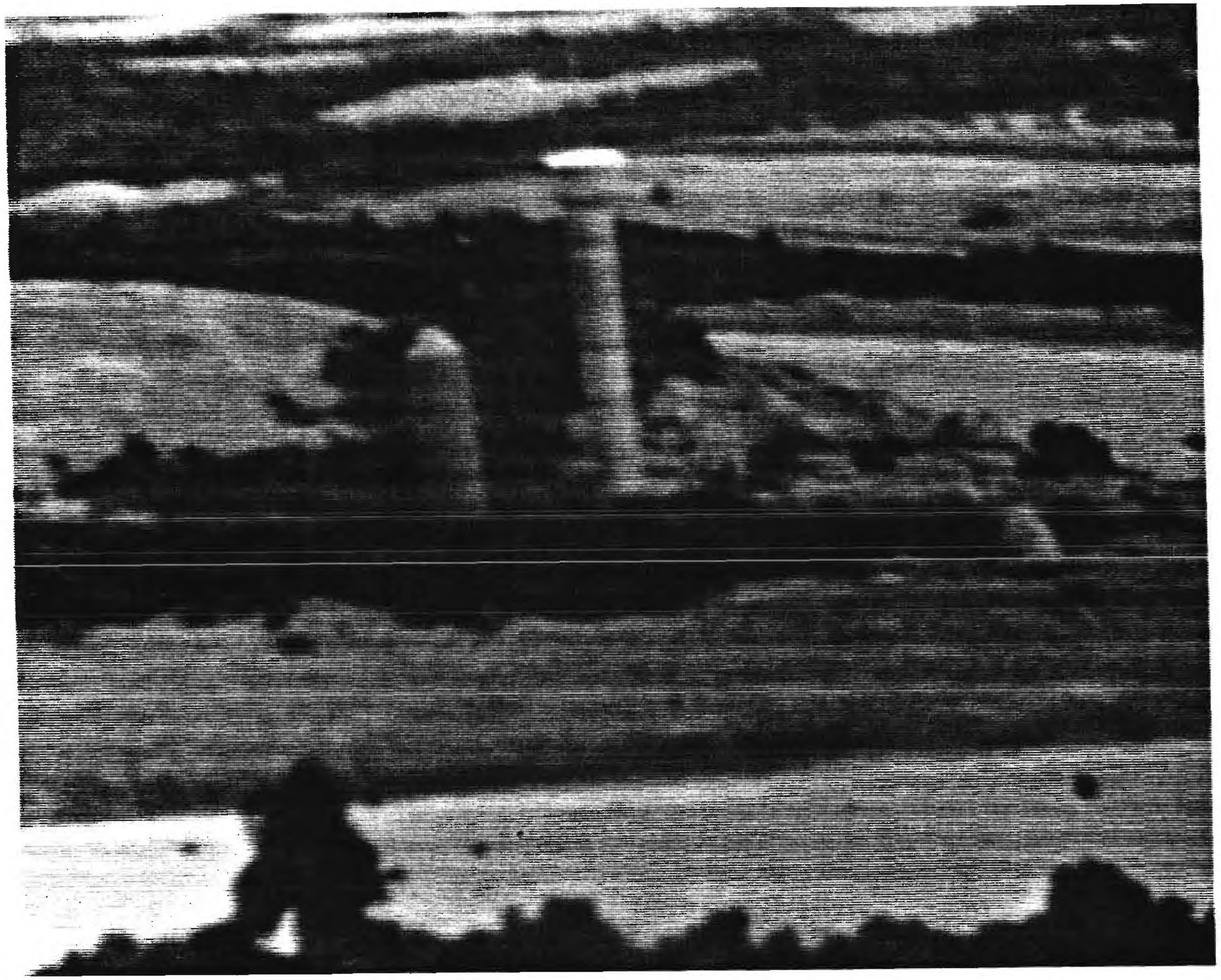

Figure 4. Simulated FLIR Tower Sequence Image

Figure 5. Edge Map Produces With A Contrast Factor of 0.1

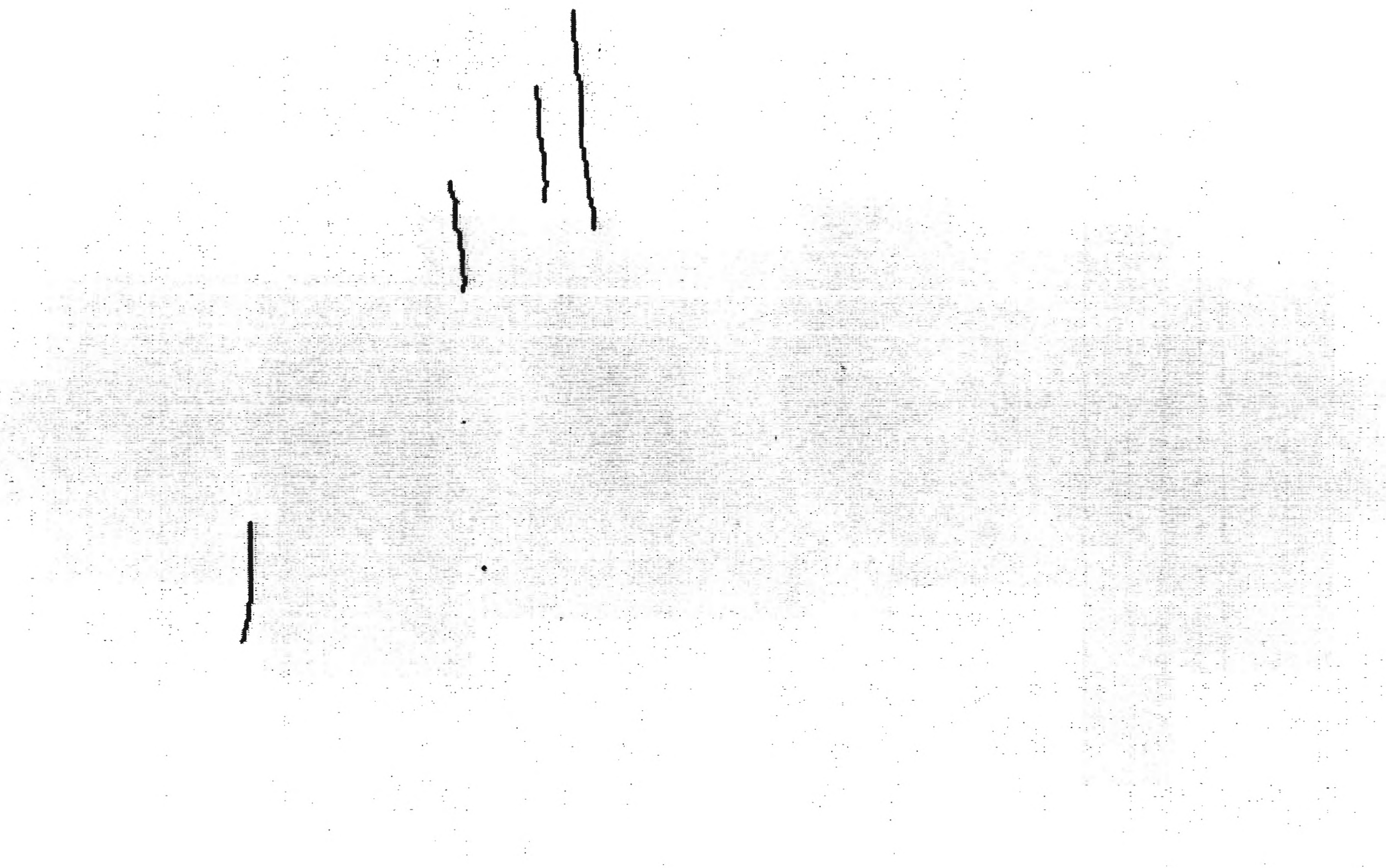

Figure 6. Non-Vertical Edge Suppression

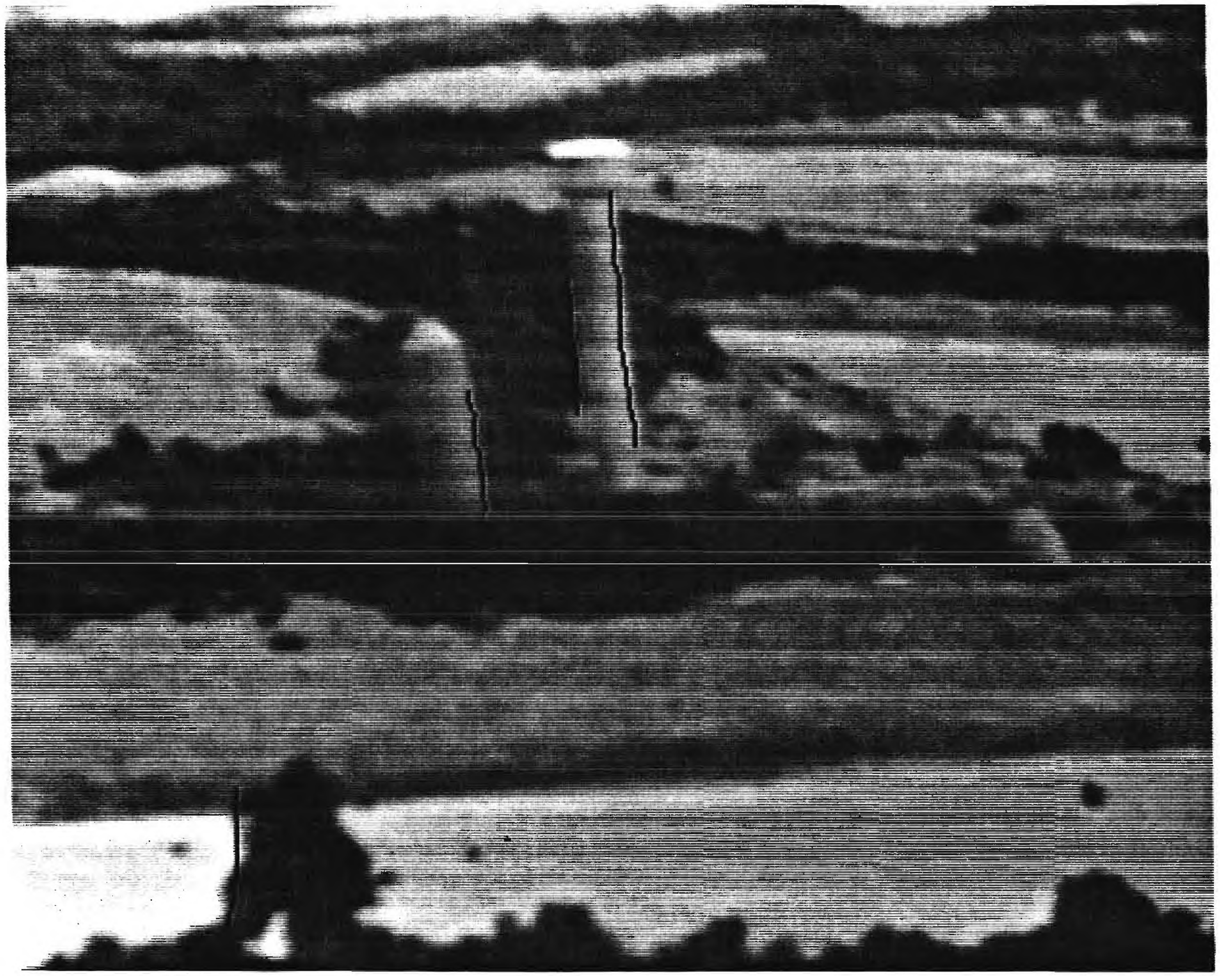

Figure 7. Tower Detection Results

TABLE 1. STRA SEQUENCE

Image	Center Range (m)	Image	Center Range (m)
00	2057.1	13	1168.2
01	1992.2	14	1243.2
02	1750.3	15	1169.7
03	1673.4	16	1021.1
04	1504.0	17	871.9
05	1427.2	18	711.4
06	1458.5	19	559.7
07	1539.9	20	408.9
08	1541.8	21	251.4
09	1721.8	22	1244.5
10	1196.0	23	0.0
11	1019.6	24	0.0
12	958.3	25	473.2

TABLE 2. STRC SEQUENCE

Image	Center Range (m)
21	332.1

TABLE 3. STRH SEQUENCE

Image	Center Range (m)	Image	Center Range (m)
01	729.7	16	559.6
02	718.3	17	546.2
03	705.9	18	537.3
04	694.6	19	905.0
05	683.3	20	912.0
06	670.3	21	919.7
07	656.7	22	930.4
08	647.0	23	932.6
09	636.9	24	939.6
10	623.2	25	944.9
11	614.5	26	955.2
12	601.6	27	965.2
13	588.9	28	974.8
14	580.5	29	988.0
15	568.0	30	996.3

TABLE 4. STRF SEQUENCE

Image	Center Range (m)	Image	Center Range (m)
20	1318.7	26	1262.8
21	1325.7	27	1251.1
22	1313.8	28	1234.2
23	1302.9	29	1221.8
24	1294.2	30	1208.9
25	1278.2	--	--

meter wide tower. Because of the forementioned database deficiencies, the tower was undetectable.

6.0 Discussion

The MUFFLIR WFOV should provide sufficient resolution to provide at least six pixels along the vertical axis of a tower structure and one pixel in the horizontal dimension at a range of 5.8 kilometers.

This information is deemed sufficient for the automatic recognition of the tower, and the range is sufficient for a lateral avoidance maneuver. Having detected an obstacle in the WFOV, it may or may not be necessary to take evasive action (i.e., to attempt to go around the obstacle), depending on the location of the object relative to the planned flight path and on the range to the object.

Since the evasive action is a lateral maneuver, it is not entirely critical that the top of the tower (a difficult point to resolve in the WFOV) be located with extreme accuracy. The algorithm requires a nominal 6 pixels in the vertical direction to detect a tower segment. The highest segment of a tower at the minimum detection range of 1.5 km which will subtend 6 full pixels is a segment which is centered 1.5 meters below the top of the tower. Thus, if a tower segment is detected within 1.5 meters of the projected position of the vehicle, evasive action is required.

Because the different sections of a tower are not distinctive (one section of the tower may appear similar to several other sections of the tower) and because the obstacles of interest will lie rear the center of the

FOV (where accurate ranging is most difficult) it will be difficult to passively range to points on the tower. This is of little consequence, however, since the range to the tower can be inferred from the fact that it is visible. (Due to the limited resolution of the WFOV, the tower will not become visible to the algorithms until it is closer than 5.8 kilometer range.) When the range to the tower is greater than 5.8 kilometers, the tower is not visible to the sensor, and so the range to the tower cannot be measured directly from the imagery.

7.0 Potential System Enhancements

Several system enhancements exist that would improve algorithm performance, the most obvious of which is the incorporation of accurate passive ranging information and its associated obstacle correspondence data. Combined with weather data, the ranging inputs would form an ancillary information source capable of increasing tower detection probabilities as well as reducing false alarms. This enhanced system concept is outlined in Figure 7.

Additional testing on a scenario generated database would serve to accurately analyze algorithm performance as a function of range and atmosphere attenuation. The inclusion of ground based objects such as roads in the imagery would allow the algorithm to be fine tuned against objects possessing the same two dimensional characteristics of a vertical tower.

Finally, false alarms can be further suppressed by exploiting a priori knowledge of tower characteristics along a planned flight path, when such information is available. Contextual information may be particularly useful when combined with a scene matching approach. For example, if a particular tower on the planned flight path is known to have a ten meter wide building nearby, it may be possible to detect the building at a range greater than 1.5 kilometers thus providing early warning of the tower location.

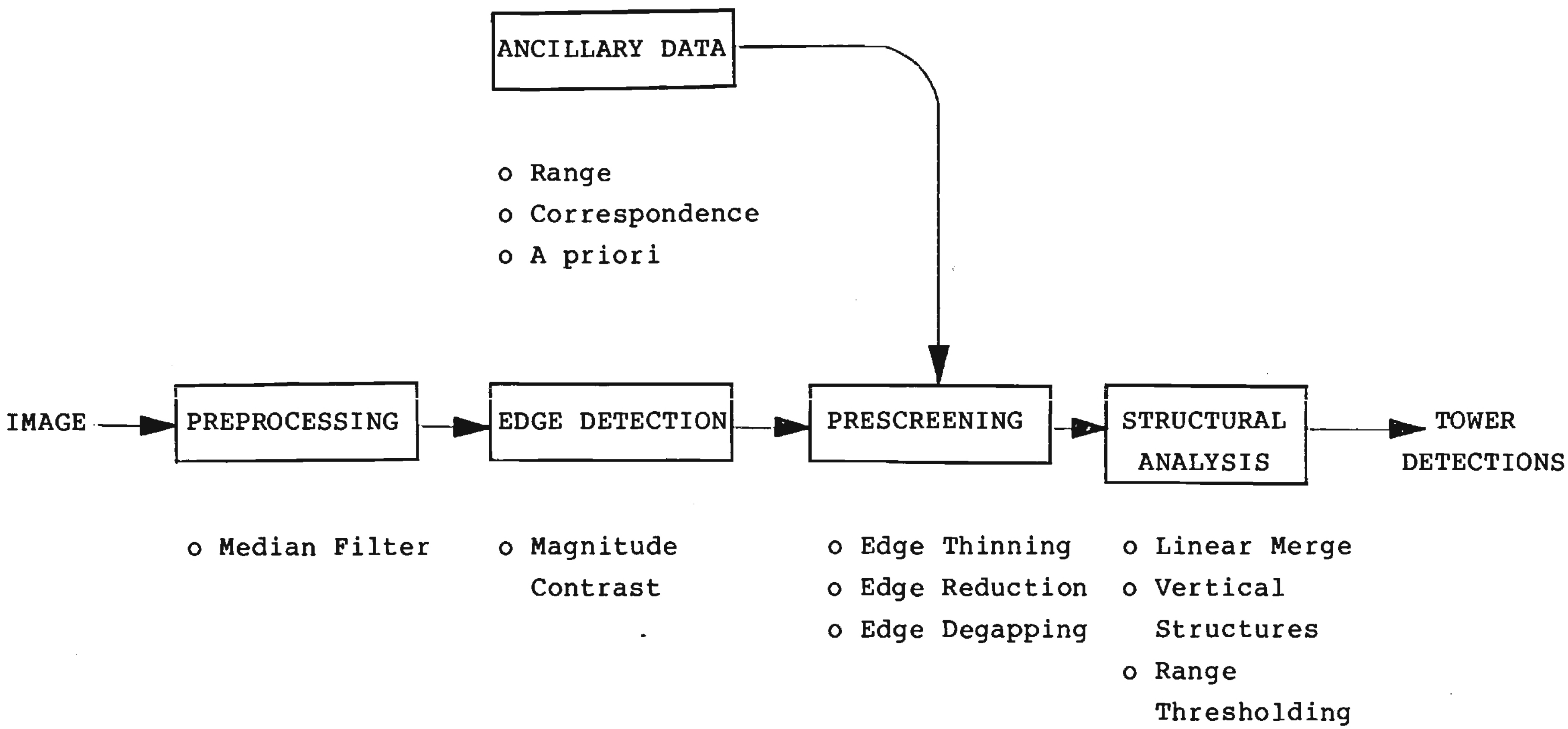

FIGURE 8. ENHANCED TOWER DETECTION ALGORITHM